Challenges and opportunities in electrochemical ironmaking

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Take Home

Iron electrolysis is the leanest technology for C-free steel

There is significant industrial examples of electrochemical production of materials to learn from

Iron chemistry calls for innovative ideas

Steel market imposes to consider the entire supply chain

Bibliography

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3. A. Allanore, "*Features and challenges of molten oxide electrolytes for metal extraction* », (2014), Journal of The Electrochemical Society, vol. 162, 13
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Electrochemical steel is not new

Paul Heroult invents the Electric Arc Furnace and Aluminum Electrolysis

Excerpt from <u>Work</u>, by Emile Zola, written in 1901

*« **Mr. Smelt** had already felt that he was threatened. He was aware of the researches which **Mr. Coulomb** was making with the view of replacing the old, slow, barbarous smeltery by batteries of electrical furnaces. The idea that one might extinguish and demolish the giant pile which flamed during seven or eight years at a stretch, quite distracted the master smelter […] However, as the cost price still remained too high for electricity to be employed for smelting ore, **Mr. Smelt** was able to rejoice over the futility of **Mr Coulombs**'s victory. »*

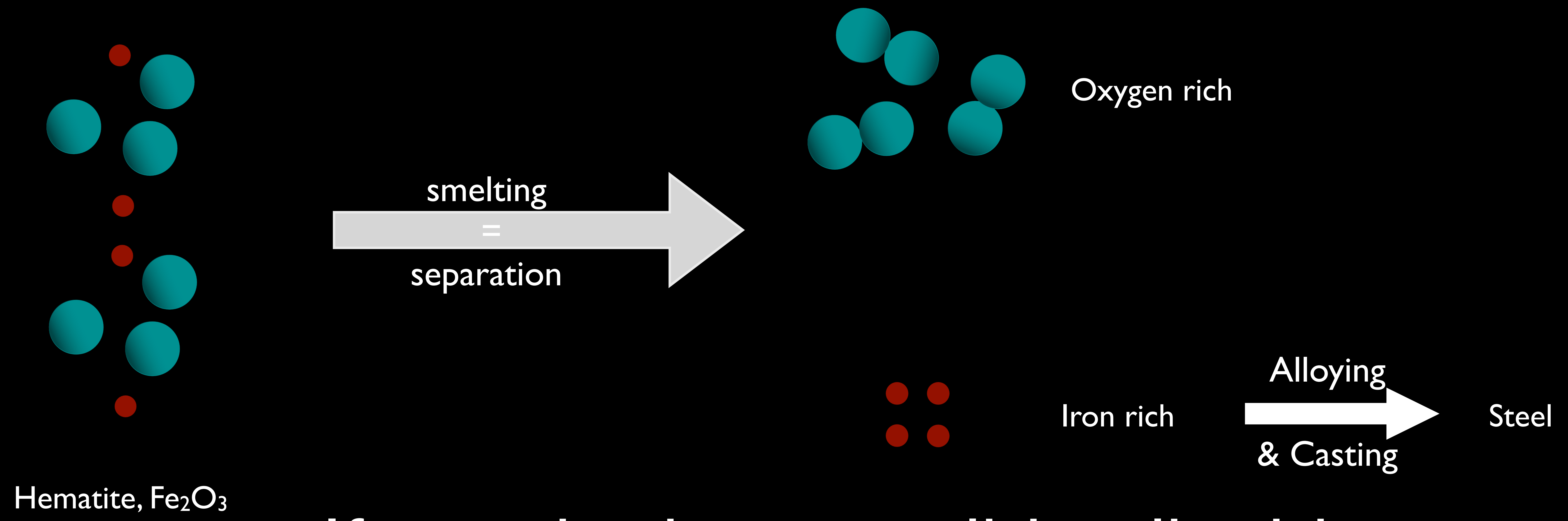
Electric Arc Furnace

Heroult 1906 (CA)

Electrochemical steel provides GHG-free steel

For example, from pure oxide to steel

$$Fe_2O_3\ _{(s)} = 2Fe\ _{(s\ or\ l)} + 3/2O_2\ _{(g)}$$



If standard state solid to liquid,
minimum energy is about 9.5GJ/t_{Fe} or 2600kWh/t_{Fe}

GHG-free electricity is directly and efficiently used

Industrial Examples

Metals are produced by electrolysis, at tonnage scale

CELL OPEX

Cell voltage

Current efficiency

$$E = \frac{\Delta V}{\phi} \frac{nF}{M_M}$$

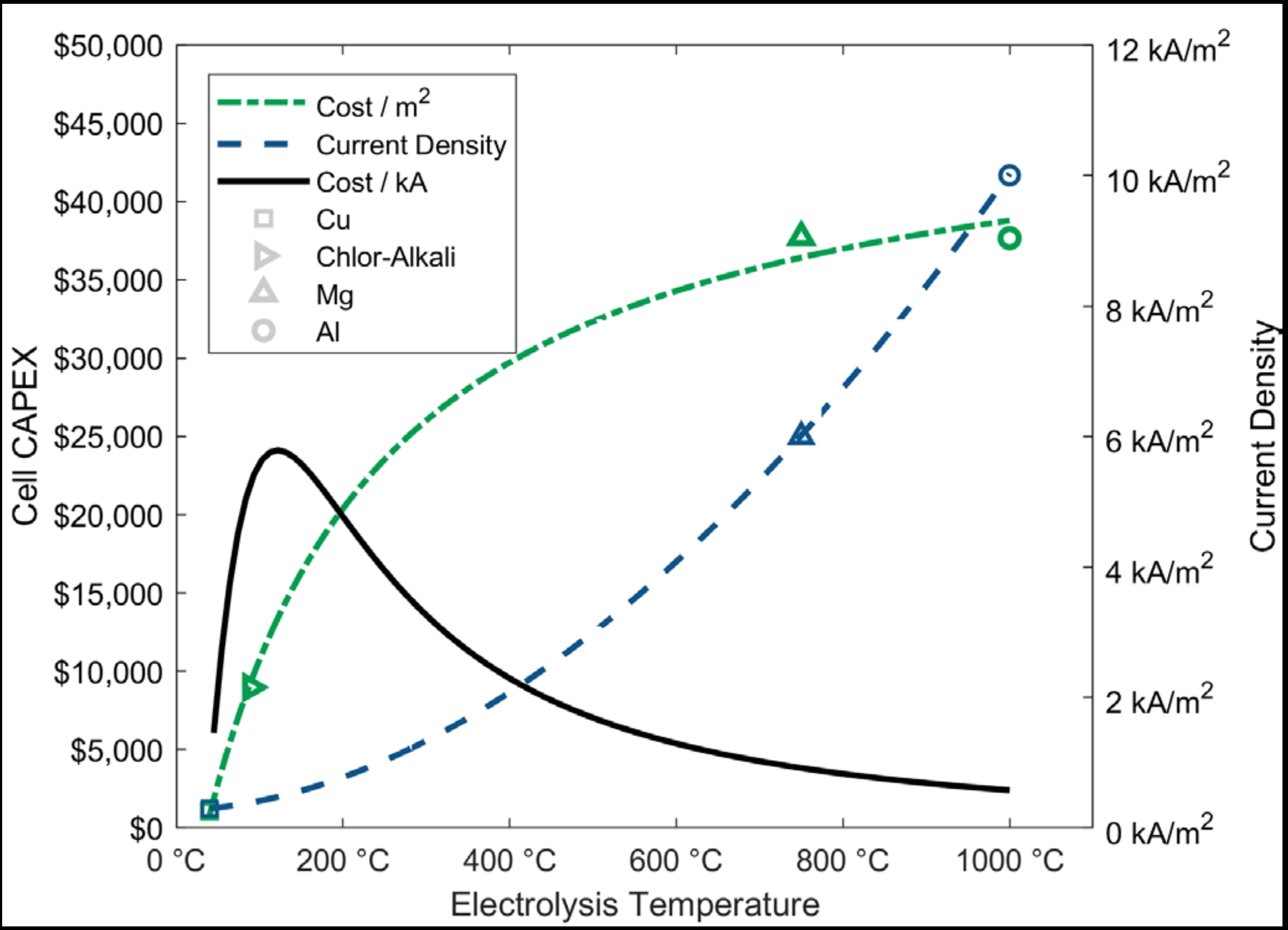
Liquid aluminium produced in molten salts

but also Ni, Co, Zn, Cu aqueous electrowinning

CELL CAPEX

$$\dot{m}_M = j \cdot S_{electrode} \cdot \frac{M_M}{nF}$$

Industrial Examples - electrolyte temperature



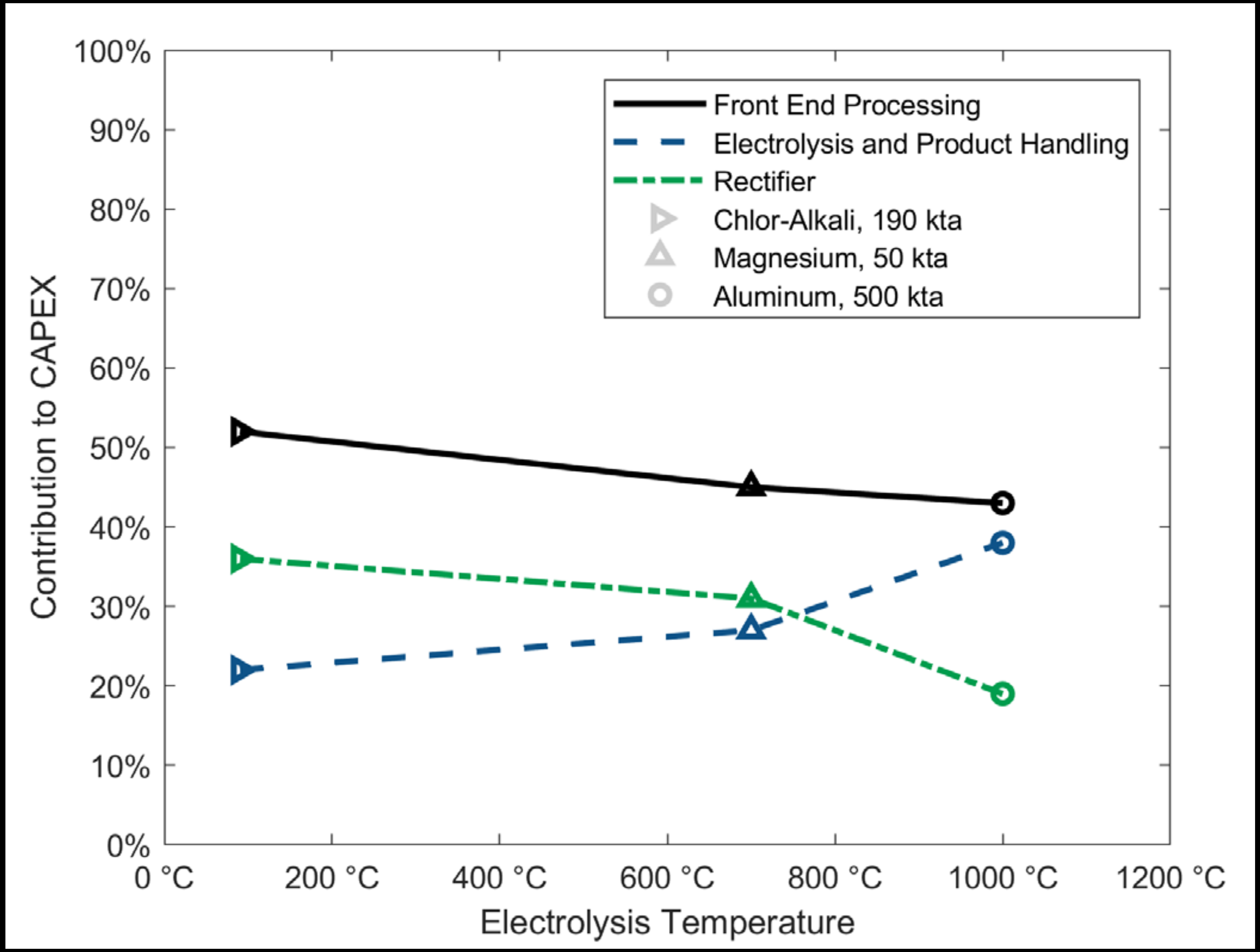
CELL CAPEX

- Not just current density
- Low-temperature

or

- Liquid metal product

Industrial Examples - beyond electrolyzer



OTHER CAPEX

- Front-end treatment makes 50% of the cost

- Rectifier costs are significant: less or larger cells favored (high-T)

- Liquid state or high temperature salts need care

Iron chemistry calls for innovative ideas

Attributes

Binding energy with O (or S) is not high compared to other metals

Can be found in relatively concentrated compound form (oxides, sulfides)

Iron (+2) becomes more stable at high temperature

Challenges

Electrodeposition of Iron is typically powdery/dendritic

Impurities in concentrates are difficult to remove

Iron compounds are « not soluble »

Existence of multiple valency (+3, +2) in most electrolyte

Iron chemistry calls for ~~innovative~~ bold ideas

« Low» temperature

Alkaline electrowinning
e.g. SIDERWIN

- NaOH - 110°C
- Iron oxide particles in suspension
- Anode and cathode solved
- Solid plates produced
- 90+ Faradaic efficiency
- High energy efficiency

« High » temperature

Molten oxide electrolysis
e.g. Boston Metal

- Molten oxides dissolve iron oxide at +1535°C
- Liquid metal product
- Various anode technologies or electrolyte possible
- Need good heat management to reach high energy efficiency

Steel market is an entire supply chain

To be cost competitive, electrolysis approach need…

- to operate between 3000 and 4000 kWh/tFe
- achieve current densities of 1 A/cm^2 or more
- need energy losses of less than 30%
- accomodate ore impurities such as SiO2, P2O5 or Al2O3
- call for cell components that lead to Capex at/less than $1000/tpa
- produce a metal product that is amenable to conventional downstream processing (continuous casting, etc…)

Perhaps it is time for a paradigm shift

Using sulfides as feedstock, either minerals or synthetic, is offering interesting opportunities

From an energetical and CO2 standpoint, Fe2S is much more promising than the oxide route

There is a wealth of opportunities, such as electric arc furnaces or even direct electrolysis that are possible

Example: molten sulfide electrolysis

Sulfidation $Fe_2O_3 + 5.5S_2 \rightarrow 2FeS_2 + 3/2SO_2$

Spontaneous and exothermic > 1000°C
Low opex with co-production of about 100kg H_2SO_4/tFe
<u>No CO_2</u>, Selective to Fe transformed in Fe^{2+}

Electrolysis $2FeS_2 \text{ -> } 2Fe(l) + 4S_2$

Only 2 electrons, minimum 2000 kWh/tFe
Production of liquid pig iron (1400°C) for steelmaking
<u>No CO_2</u>, Graphite inert anode available

Overall route consumes less energy than other options, integrates up (impurities) and down (steel) stream

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